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Are there climatic signals in fishery data for sardine (*Sardina pilchardus*) along the Iberian Atlantic coast?

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The Iberian sardine (*Sardina pilchardus*) is distributed along the whole shelf of the Iberian Peninsula with the highest catches being taken from southern Galician waters and northern Portugal. The fishery is dependent on the strength of the recruitment in this area and recruitment processes seem to be driven by a combination of oceanographic (local) and climatic (global) events. In an exploratory analysis we examined whether the variability observed in landings from ICES areas VIIIc (northern) and IXa (western Iberia) from 1940 to 2005, and in estimated annual recruitment and spawning stock size for the whole stock could be related to environmental conditions at large and local scales, taking into account temporal autocorrelation in the response variables. Landings for areas VIIIc and IXa show differing trends and were most strongly related, respectively, to the multi-decadal Atlantic oscillation (AMO) and to SST (with an optimum around 15^{o} C). Recruitment was negatively related to air temperature (AT). We stress the need for taking into account time lagged effects, non linear relationships, autocorrelation in response variables and collinearity between explanatory variables. We discuss possible mechanisms underlying these observed patterns and whether the apparent climatic relationships have any predictive value.

Introduction

Population dynamics of short-lived marine species such as cephalopods and small pelagic fish depend heavily on recruitment success due to the small number of older age classes present. In species that are under fishing pressure, good recruitment to the fished part of the population has an even greater role in sustaining the population, since an already high natural mortality is augmented by exploitation and new recruits can form a substantial proportion of the exploited stock of the year (up to 100% in annual cephalopods). Recruitment failure over several successive years (or in the shortest-lived species, even a single year) can lead to stock collapse (c.f. the anchovy crisis in the Bay of Biscay, Borja et al., 2008).

Recruitment fluctuations are a characteristic of many of the populations of small pelagic fish (e.g. Lluch-Belda et al., 1989; Schwartzlose et al., 1999 for a review) and cephalopods (e.g. Pierce et al., 2008) studied around the world, including the European sardine *Sardina pilchardus* (Waulbaum, 1792). Sardine, a small shoaling pelagic species distributed in the Atlantic from Mauritania and Senegal in the south to the North Sea in the north (Parrish et al., 1989), supports an important directed fishery in both Portugal and Spain with annual landings of around 100 thousand tonnes in recent years (ICES, 2009). The Iberian sardine is considered a single stock for management purposes, delimited by Spanish-French border in the North and the Strait of Gibraltar in the south (ICES, 2009). The highest catches are taken in ICES subdivision IXa (Portuguese and South Galician waters) but there are also substantial catches from VIIIc (northern Galician and Cantabrian waters).

Periods of good sardine recruitment have encouraged development of new industries and have led to significant social and economic changes. In Galicia, sardine was very abundant, easily available and constituted a cheap source of proteins that attracted large numbers of entrepreneurs from Cataluña in the second half of the 18th century, It is estimated that near 15000 Catalonians moved to Galicia and brought with them the know-how to revolutionise the fishery and laid the foundations for a globally important canning industry, which in turn increased the demand for the fish. Conversely, periods of low recruitment negatively affected both the fishery and the industries depending on it and were felt as "crises" due to their economical and social repercussions. Such periods were recorded from 1876 to 1895, 1924 to 1925, 1941 to 1942 and in 1946 to 1957 (see Wyatt and Porteiro, 2002 for a review). Fluctuations in the fishery continued with landings in both Portugal and Spain reaching a maximum in 1960s, followed by an all time low at the end of the 1990s which was particularly felt in Galicia.

There have been several attempts to understand the possible causes for this variability in landings, mainly since the last crisis at the end of the 1990s (Dickson et al., 1988; Guisande et al., 2001, 2004; Borges et al., 2003; Cabanas et al, 2007). These studies explored the relationship between environmental variables, at large and local spatial scales, and sardine recruitment in the Galician and Portuguese sardine fishery - and obtained varied results. Portuguese sardine catches have been found to be negatively correlated with northerly winds in two separate analysis using different landing series (Dickson et al., 1988 and Borges et al., 2003). In the latter study, the authors found that this negative effect of winds on catches was strongest for a time lag of 6 to 18 months. Parallel analysis carried out with juvenile sardine landings in Galician has explained part of the variability in landings as a function of the Ekman transport in the area and the NAO (Guisande et al., 2001, 2004). Finally, Cabanas et al. (2007) used several environmental indices (NAO, variability in the position of the Gulf Stream, upwelling strength and the poleward current) to explain the variability in sardine stock recruitment from 1978 to 2005. The fitted model matched quite well the predicted recruitment during the 1980s but when the whole time series was considered the performance of the model was poor.

Data on landings of sardine in the Iberian Peninsula are available back to 1946. Modern day stock assessments extend back only as far as 1978 so the landings series potentially allows exploration of environmental influences on the population much further back. In studies of any fished species, fishery data have some obvious advantages over survey data, i.e. that they are based on extensive sampling of the population and long time series of catches are available for many species. The disadvantages of this type of data have also been widely discussed and include the influence of socioeconomic and technological considerations such as the price of the catch, costs of fishing, development of new gears and technological aids, changes in fishing effort and methods, etc., (Fox and Starr, 1996).

Minimally, information derived from fishery data can augment research data and improve estimates of the distribution and relative abundance of commercial fish species (Fox and Starr 1996). In short-lived species, fishery catches are arguably likely to be more closely related to abundance than in long-live species: (a) interannual variation in population size is relatively high so that availability is a key determinant of numbers caught, (b) fishing effort is more likely to be directed elsewhere in years of low abundance since fishermen targeting short-lived species are aware of the need to diversify into catching other species to maintain their income, (c) there is less use of output controls (quota restrictions) because stock abundance is more difficult to predict.

In the case of sardine, the stock is not managed through TACs but through a series of regulatory measures that were introduced in the late 1990s to protect the stock and decrease the fishing effort: limits to daily catches and number of days fishing, and establishment of minimum landing sizes. Since sardine is a short-lived species, demand remains high and there are no quota restrictions on landings, the fishery is likely to react quickly to changes in abundance. Catch data may therefore reveal coherent large-scale fluctuations in abundance.

Currently available statistical modelling methods (e.g. GAMs, GAMMs) allow common trends in fish abundance and environmental series to be identified and enable the construction of robust models that take into account temporal autocorrelation (see, e.g. Zuur et al., 2007, 2009). The wide availability of relevant oceanographic and other environmental time series facilitates testing of plausible hypotheses about sardine abundance.

The objectives of this study were therefore to determine whether sardine landings, recruitment and spawning stock biomass are related to local oceanographic conditions and/or large-scale ocean climate indices.

Methods

Data sets, data processing, data exploration

The sardine landings series (response variables) were all annual totals, as follows: (a) catches in area VIIIc, (b) catches in IXa, (c) total catches from VIIIc and IXa (1946-2006) and (d) landings of "*xouba*" in Vigo (1978-2005). *Xouba* is the name given to young sardines (0 and 1 year old fish) which constitute a separate market category that attains a higher price. Estimated spawning sock biomass for the IberoAtantic sardine (1978-2007) and estimated recruitment both derive from ICES (ICES, 2009). Fishing effort and CPUE data are not available. Histograms and QQ-plots of the response variables indicated approximately normal distributions except for recruitment, which was log-transformed accordingly. Response variables were also checked for autocorrelation and appropriate ARIMA models fitted to obtain series of non-autocorrelated residuals.

Local environmental indices included sea surface temperature (SST), air temperature (AT), wind strength (W) and its westerly and components west (U) and, north (V) for 42ºN 10ºW, all taken from the COADS database (http://icoads.noaa.gov/). Annual, monthly, and six-monthly (April-September and October-March) indices were extracted. In addition, an upwelling index (Iw) was computed for a point off the Galician coast using the atmospheric pressures (April-September) provided by the Spanish National Meteorological Institute (see Lavin et al., 1991).

Large scale atmospheric and oceanographic conditions were represented by three indices:

- The NAO index (http://www.cru.uea.ac.uk/cru/data/nao.htm), which was split in two components. *NAOwinter* (between December of the preceding year and March of the present year) coincides temporally with the main spawning time of sardine off Western Iberian Peninsula. *NAOspring* (from March to May), corresponds with the main spawning period in the Cantabrian Sea.

- The Gulf index is an annual index of the variability in the position of the Gulf Stream (http://web.pml.ac.uk/gulfstream/data.htm)
- The Atlantic Multidecadal Oscillation (AMO), which is basically an index of the North Atlantic temperatures (http://web1.cdc.noaa.gov/Timeseries/AMO/)

All explanatory variables were checked for collinearity and for cross-correlation with response variables. Since relationships between response and explanatory variables are not necessarily linear, GAMs were also used to explore relationships at different time-lags.

Time series analysis

We used minmax autocorrelation factor analysis (MAFA), as implemented in BRODGAR (Highland Statistics Ltd) to further explore relationships between explanatory and response variables. MAFA extracts common trends from response time series and determines (linear) correlations between the common trends and the explanatory variables. It is a PCA-type analysis in which the axes represent trends (Shapiro and Switzer, 1989; Solow, 1994). In PCA, the first axis explains most variance. In MAFA, the first axis has the highest auto-correlation with lag 1. The second axis has the second highest auto-correlation with time lag 1, etc. The underlying idea is that a trend is associated with high auto-correlation with time lag 1. Therefore, the first MAFA axis represents the trend, or the main underlying pattern in the data. This axis can also be seen as an index function or smoothing curve. In the present application, both response and explanatory variables showed variation in range so all were normalised for these analyses.

Generalised additive models

GAM was used to further quantify relationships suggested by the exploratory and time-series analyses, in this case relationships between individual response variables (landings series, recruitment, SSB or the residuals from ARIMA 1,0,0 models) and the suite of putative explanatory variables. Guided by the MAFA results, annual SST and AMO were selected as the most likely explanatory variables. Forwards selection was used due to the high collinearity between some explanatory variables. At each step, non-significant variables were dropped and an additional variable added. Residuals were checked for autocorrelation. GAMs were also fitted to SSB and recruitment data, in this case allowing any environmental series and SSB or recruitment to be included as explanatory variables.

It should be noted that when an autocorrelated response series is modelled using an autocorrelated explanatory variable, model residuals may or may not be autocorrelated. If they are not, the resulting model is statistically satisfactory and it can be implied that autocorrelation in the response variable was entirely due to autocorrelation in the explanatory variable. However, in biological terms this does not necessarily make sense. It is highly likely that autocorrelation in sardine landings is a function of sardine population dynamics (and fleet dynamics) and not purely a consequence of environmental conditions. Consequently these model results need to be treated with caution. Using ARIMA residuals as the response variable allows environmental effects on landings to be examined once the autocorrelation component of the response series has been removed.

Results

Simple correlations and cross correlations between explanatory variables

Landings for area IXa make up on average 82% of total landings from areas VIIIc and IXa combined and are unsurprisingly highly correlated with total landings. Landings of *xouba* in Vigo represent only around 1% of the overall total. All three separate landings series (VIIIc, IXa, xouba) were significantly positively correlated with each other but the highest value (0.539) was sufficiently low that it was considered appropriate for all three series to be analysed separately. The landings series for VIIIc and IXa were significantly correlated with annual spawning stock size while *xouba* landings were correlated with recruitment (Table 1). Among the suite of candidate explanatory variables, collinearity was generally rather high, and SST and AT were the most highly correlated with each other.

Table 1. Correlations between response variables: annual landings (L) series, spawning stock size and recruitment: values for R and (in parentheses) probability.

	L total	**L VIIIc**	**L IXa**	**L *xouba***	**Recruitment**
L VIIIc	0.588 (0.000)				
L IXa	0.962 (0.000)	0.344 (0.007)			
L *xouba*	0.560 (0.002)	0.464 (0.013)	0.539 (0.003)		
Recruitment	0.350 (0.063)	0.330 (0.080)	0.328 (0.083)	0.674 (0.000)	
SSB	0.589 (0.001)	0.370 (0.048)	0.601 (0.001)	0.170 (0.387)	-0.113 (0.561)

Cross correlation analysis indicated that total landings are strongly correlated at lags 0 and 1 to SSB (SSB is highest in the year following high landings) and to a lesser extent to recruitment. Therefore, models of landings could include SSB and recruitment as explanatory variables. However, the SSB series is considerably shorter so data before 1978 would be lost. In addition, when SSB and recruitment were used as explanatory variables (with lag 0) in a GAM for total landings, although both had significant effects ($P<0.0001$ and $P=0.0003$ respectively), model residuals were autocorrelated. Nevertheless it may be noted that total landings were positively and linearly related to SSB while showing an asymptotic relationship with recruitment (Figure 1).

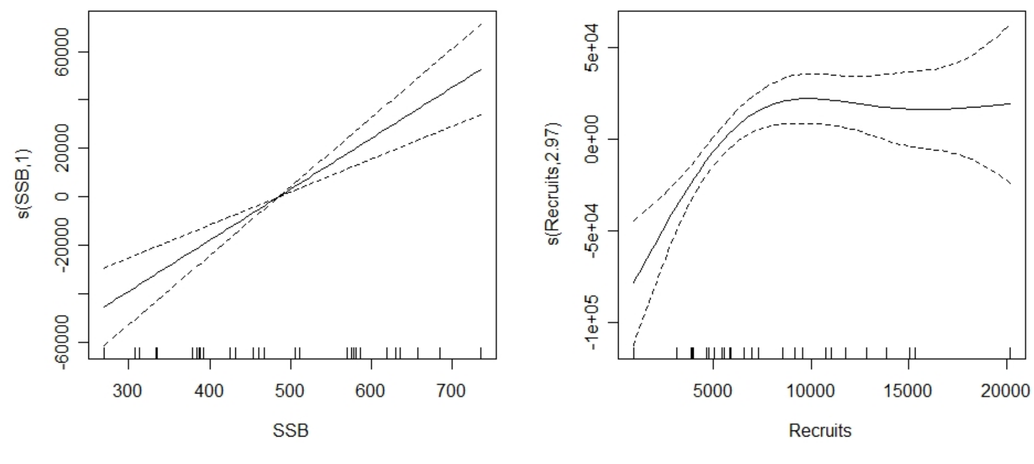

Figure 1. Smoothers for a GAM of total landings in relation to SSB and recruitment.

Autocorrelation in response variable series

Total landings showed significant autocorrelation at lags 1-3 years but significant partial autocorrelation only at lag 1, indicating that an ARIMA (1,0,0) model could be fitted. In the fitted model, the term AR1 (autoregressive term for lag 1) is highly significant (T=13.88, P=0.000) and the residuals are free of autocorrelation. Similar results were obtained for the VIIIc and IXa series. In both cases an ARIMA (1,0,0) model was a satisfactory fit and model residuals were free of autocorrelation. In the case of the *xouba* series, the only significant autocorrelation was at a lag of 4 years but the time series was insufficiently long to fit an appropriate ARIMA model. The recruitment series showed no significant autocorrelation[1], while an ARIMA (1,0,0) model could be fitted to the SSB series. In the fitted model, the term AR1 is highly significant (T=5.83, P=0.000) and the residuals are free of autocorrelation.

Cross-correlations between response and explanatory variables

Cross correlation analysis indicated that (linear) relationships between sardine landings and SST were generally negative and strongest at lags between 1 and 7 years (Figure 2). The landings series were also correlated with AMO, with highest correlations at positive lags (AMO follows landings) but also significant correlation at zero lag. Cross-correlations for other explanatory variables were generally weak.

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             -1.0 -0.8 -0.6 -0.4 -0.2  0.0  0.2  0.4  0.6  0.8  1.0
             +----+----+----+----+----+----+----+----+----+----+
-15  -0.057                            XX
-14  -0.072                           XXX
-13  -0.139                          XXXX
-12  -0.150                         XXXXX
-11  -0.168                         XXXXX
-10  -0.303                     XXXXXXXXX
 -9  -0.336                     XXXXXXXXX
 -8  -0.410                   XXXXXXXXXXX
 -7  -0.459                  XXXXXXXXXXXX
 -6  -0.415                   XXXXXXXXXXX
 -5  -0.362                    XXXXXXXXXX
 -4  -0.384                   XXXXXXXXXXX
 -3  -0.383                   XXXXXXXXXXX
 -2  -0.394                   XXXXXXXXXXX
 -1  -0.425                  XXXXXXXXXXXX
  0  -0.376                    XXXXXXXXXX
  1  -0.313                     XXXXXXXXX
  2  -0.217                        XXXXXX
  3  -0.180                         XXXXX
  4  -0.189                        XXXXXX
  5  -0.216                        XXXXXX
  6  -0.245                       XXXXXXX
  7  -0.176                         XXXXX
  8  -0.161                         XXXXX
  9  -0.172                         XXXXX
 10  -0.162                         XXXXX
 11  -0.200                        XXXXXX
 12  -0.152                         XXXXX
 13  -0.138                          XXXX
 14  -0.033                            XX
 15   0.043                             XX
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Figure 2. Cross-correlation output for total landings in year t and annual SST in year t+k.

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[1] However, when the series is extended to 2008, an autocorrelation at a time-lag of 4 years becomes marginally significant and an ARIMA (4,0,0) model (without a constant) fitted to the data has a significant AR4 term.

The time lagged links to SST need to be treated with caution since the strongest linear relationship is not necessarily the strongest relationship. In a GAM (i.e. allowing non-linear relationships), the strongest relationships between IXa landings and SST were for lags of zero and 7 (based on F and p values). Taking % deviance explained into account, the best model is for zero lag (Table 2). The shape of the relationship shifts from a smoother with a peak around 15.3^{o} C (at zero lag) to a simple linear negative relationship (at lag 7).

Table 2. GAM output for models relating IXa landings to SST at various time lags.

Lag (years)	**edf**	**F**	**p**	**% deviance explained**
0	3.549	6.173	0.00035	30.4%
1	2.537	5.34	0.00102	26%
2	2.431	5.041	0.00154	25.6%
3	2.013	3.662	0.0103	19.8%
4	2.341	3.245	0.0186	17.5%
5	1.894	2.758	0.0371	15%
6	1.224	4.368	0.00805	16.9%
7	1	14.94	0.00031	22.3%

MAFA results

MAFA was applied to the three normalised landings series for VIIIc, IXa and *xouba* in Vigo. Of two common trends, the first shows two cycles, with a midpoint around 1975, and the second has its strongest peak in 1975. Essentially the first trend is dominated by IXa landings, the second by VIIIc landings (Figure 3). Trend 1 is related to both SSB and recruitment.

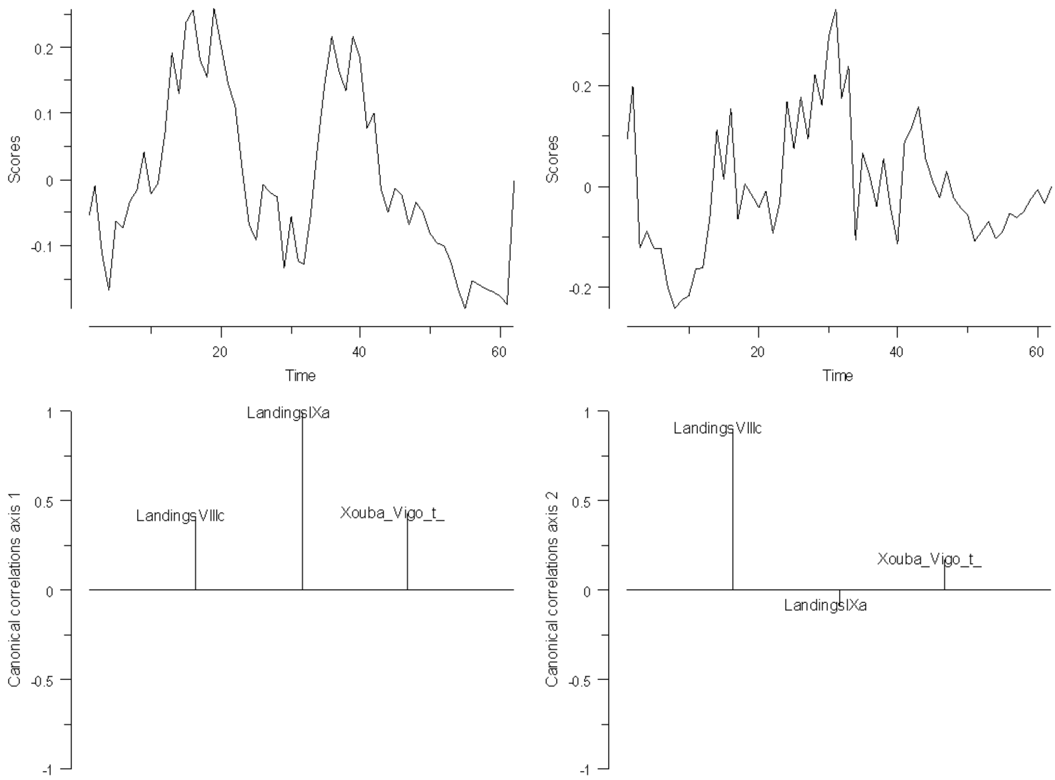

Figure 3. MAFA for landings: common trends 1 (top left) and 2 (top right) and canonical correlations for trends 1 (bottom left) and 2 (bottom right).

Re-running the MAFA for the landings series but with environmental explanatory variables, trend 1 (driven by IXa landings) is seen to be related to SST, AT and wind. Trend 2 (driven by VIIIc landings) is related to LW and AMO (Table 3).

Table 3. Correlations between explanatory variables and MAFA common trends 1 and 2. Significant correlations are shown in bold face.

Variable	Trend 1	Trend 2
SST_Apr_Se	**-0.3360**	-0.2290
SST_Oct_Ma	**-0.2845**	-0.1920
AT_Apr_Sep	**-0.3310**	-0.2035
AT_Oct_Mar	**-0.2972**	-0.2093
W_Apr_Sep	**-0.2388**	0.0563
W_Oct_Mar	-0.1729	0.1539
U_Apr_Sep	0.0277	-0.0445
U_Oct_Mar	0.1462	0.1382
V_Apr_Sep	0.1582	-0.0531
V_Oct_Mar	0.1344	0.0418
GULF_Annua	-0.0725	-0.3108
NAO_w	-0.0673	0.0238
NAO_mam	0.0997	0.0018
LW_Apr_Sep	0.0389	**0.4363**
AMO	-0.1758	**-0.5097**

Additional MAFAs were run for explanatory variables, firstly for annual oceanographic indices and large-scale indices, the second including seasonal oceanographic indices. The main trend is directional up to the mid-1990s, but the second trend matches the main trend in the catch series in having a trough in 1975. Trend 1 is most related to W (which shows a fairly consistent upward trend over most of the period, although also to SST) while trend 2 particularly relates to AMO (Figure 4). MAFA results for seasonal oceanographic indices (not shown) were rather similar, with very similar common trends, related most strongly to wind and AMO.

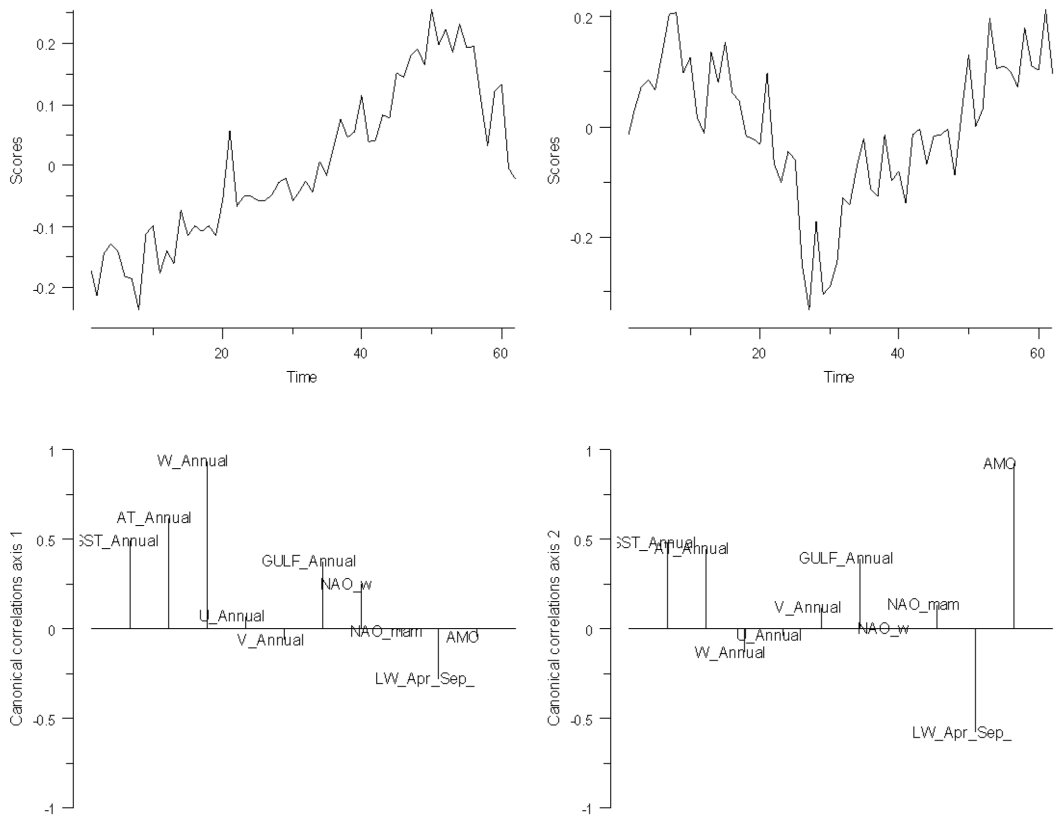

Figure 4. MAFA for annual environmental indices: common trends 1 (top left) and 2 (top right) and canonical correlations for trends 1 (bottom left) and 2 (bottom right).

Generalised additive models for environmental effects

We fitted GAMs to the four landings series (or the residuals from ARIMA models) using either environmental predictors only (this section) or a combination of environmental series and SSB (see below) (Table 4). Only environmental variables highlighted as important by MAFA were used (SST, AMO) in the forward selection process.

The only environmental variable in the best model for total landings was annual SST, with the smoother indicating an optimum temperature around 15.3^{o} C (Figure 5). However, significant autocorrelation remained in the residuals.

In the case of IXa landings, again the best model was that containing SST only, again indicating an optimum temperature of around 15.3^{o} C. In this case however, model residuals contained no significant autocorrelation. In the case of VIIIc landings, the best model included AMO (which had a negative and linear effect) and residuals were not autocorrelated. The model for *xouba* included a negative linear effect of SST and residuals showed no autocorrelation.

Three of these four models were re-run using ARIMA residuals from the response series (no ARIMA could be fitted to *xouba* landings). In the case of total landings residuals, the best model includes only a marginally non-significant effect of SST (P=0.071), the smoother shape indicating an optimum temperature around 15.2^{o} C (not shown). No satisfactory model could be fitted to residuals from the IXa landings while for the VIIIc landings the result was very similar to that for total landings residuals, i.e. the was a marginally non-significant effect of SST (P=0.082) and the smoother shape indicating an optimum temperature around 15.2^{o} C (not shown).

Table 4. Summary of GAMs fitted to landings series, indicating the landings series selected, which variables were used as predictors, and two measures of model quality (deviance explained and autocorrelation in residuals).

Response	**Explanatory variables**	**Variables in final model**	**Deviance explained**	**Autocorrelation in residuals?**
Total landings	Environmental	SST (P<0.0001)	37.3%	Yes
IXa landings	Environmental	SST (P=0.0004)	30.4%	No
VIIIc landings	Environmental	AMO (P<0.0001)	29.9%	No
xouba landings	Environmental	SST (P=0.0097)	23%	No
Total landings	Env + stock	SST (P=0.0057) SSB (P=0.0007)	62.9%	Yes
IXa landings	Env + stock	SST (P=0.015) SSB (P=0.0005)	61.5%	Yes
VIIIc landings	Env + stock	-	-	-
xouba landings	Env + stock	-	-	-
TL residuals	Environmental	SST (P=0.0712)	12.5%	No
IXa residuals	Environmental	-	-	-
VIIIc residuals	Environmental	SST (P=0.082)	11.6%	No

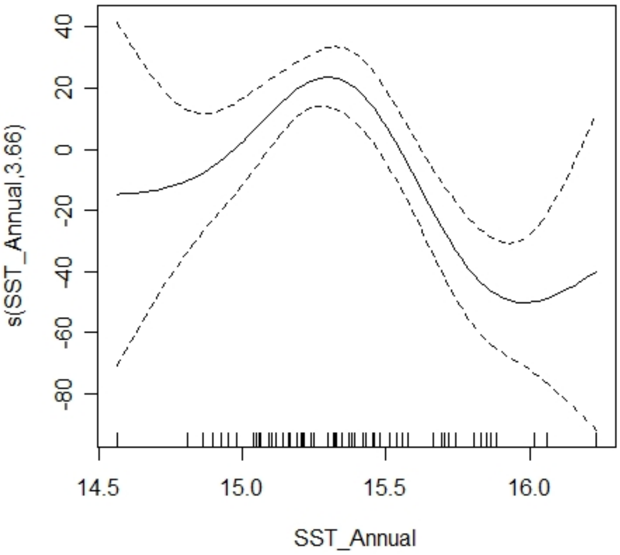

Figure 5. Smoother for effect of annual SST on total landings.

Generalised additive models for environmental and stock effects

The best initial models for both total landings and IXa landings include annual SSB (positive, linear) and SST (negative linear) effects but the residuals are autocorrelated in both cases. The latter model has a higher deviance explained than the model with only SSB but is poorer in that residuals are autocorrelated. In the case of VIIIc landings, addition of SSB to the pure environmental model (with AMO) results in no improvement. Similarly, for *xouba* landings, addition of SSB to the pure environmental model (with SST) results in no improvement.

Generalised additive models for recruitment and SSB

Following a similar approach to that used for the landings series, models were fitted as summarised in Table 5. In this case, the full suite of available explanatory variables was considered and both variables (SSB and recruitment) were also considered as possible predictors of the other.

Table 5. Summary of GAMs fitted to SSB and recruitment series, indicating the response series selected, which variables were used as predictors, and two measures of model quality (deviance explained and autocorrelation in residuals).

Response	**Variables in final model**	**Deviance explained**	**Autocorrelation in residuals?**
Recruitment	AT (P=0.0045)	27.2%	No
SSB	SST (P=0.0198)	19.2%	Yes
SSB residuals	SST (P=0.0571)	13.2%	No

Recruitment (log-transformed) was apparently unrelated to stock size in the same or previous year but it was related to temperature in the same year. Although the result was similar using SST as the predictor, the strongest relationship was with AT (P=0.0045). This relationship was linear and negative. There was no significant autocorrelation in the residuals.

SSB showed a weak negative linear relationship with annual SST (P=0.0198) but strong autocorrelation remained in the residuals. Fitting a model to the ARIMA residuals of SSB, the negative linear effect of SST remained but was marginally non-significant (P=0.0571).

Discussion

There have been numerous previous analyses of relationships between the state of the Iberian sardine and environmental conditions and there seems to be a consensus that environmental signals are present. Previous studies have used various different datasets and various techniques – differing for example in whether they accounted for non-linear relationships, different time-lags and controlled for autocorrelation. The analysis presented here shows that each of these three issues is important.

It is in the nature of such analyses that conclusions tend to vary according to the datasets used (see Solow 2002). At the time of completion of the present analysis, we were using the longest time series available. Since then, the extended recruitment series available already allows detection of a 4-year cycle that was not previously significant (a cycle that does appear in the *xouba* landings series in the present analysis).

Given the high collinearity between different environmental series, it can be difficult to decide on the basis of purely empirical models which environmental factors are more important in determining fish abundance. The present analysis highlights the importance of temperature (as SST, AT or AMO) whereas, for example, Borges et al. (2003) highlighted the importance of northerly winds. Our analysis highlighted an issue with the most readily available wind strength dataset (it shows an implausibly steady upward trend in recent years) and we will need to repeat the analyses with corrected wind strength data. In most if not all cases, plausible mechanisms can be hypothesised to explain the observed empirical links and there is no doubt that research on mechanisms by which the environment affects the fish are crucial to improve our understanding of the processes. However, such studies, if successful, may not provide a panacea: the environment in which fish live is intrinsically multidimensional and it may simply be wrong to assume that a single process is the most important one (Carrera and Porteiro, 2003).

When using landings data as a response variable we might, *a priori*, expect that there will be effects of population dynamics, fleet dynamics (and fishery regulations) and environmental factors. The landings of small sardine in Vigo (*xouba*) are expected to relate more closely to recruitment while total landings would be expected to reflect total stock size.

Our results found no evidence of a stock recruitment relationship, consistent with previous studies. Landings of *xouba* were related to recruitment, as found by previous studies (e.g. Robles et al., 1992; Cabanas et al., 2007) and also showed a four-year cycle, a cycle subsequently shown to occur in recruitment. Recruitment was higher in cooler years (low AT), an effect explaining around 25% of variation in recruitment strength.

Our results suggest that landings data contain a strong signal for stock abundance (or at least done so until now) and, further, that trends in areas VIIIc and IXa are somewhat different. The latter (the larger component of the stock) showed a trend that resembles a 30-year cycle, with a trough in 1975 and another one in the present day. Around 30% of this variation relates to SST, with highest landings recorded at an average local annual SST of around 15.3^{o}C and both warmer and cooler temperatures being associated with lower landings. In contrast, in area VIIIc, a broader temperature index (AMO) was more useful and indicated a negative effect of higher temperatures, again explaining around 30% of variation. Statistically, the goodness of fit of these models was adequate and the residuals contained no autocorrelation. However, biologically speaking, the fact that these models account for autocorrelation is not completely convincing. Models fitted to residuals from ARIMA (1,0,0) models of the main landings series, i.e. the part of the landings signal not related to autocorrelation, suggested that an effect of temperature was still present (indeed the estimated optimum value is a very similar 15.2^{o} C) but statistical significance was marginal.

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